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# Statistical Analysis of a Large Sample Size Pyroshock Test Data Set Including Post Flight Data Assessment

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July 2010

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# Statistical Analysis of a Large Sample Size Pyroshock Test Data Set Including Post Flight Data Assessment

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## Abstract

The EOS Terra spacecraft launched on an Atlas IIAS launch vehicle on its mission to observe planet Earth in late 1999. Prior to launch, the new design of the spacecraft's pyroshock separation system was characterized by a series of thirteen separation ground tests. The analysis methods used to evaluate this unusually large amount of shock data will be discussed in this paper, with particular emphasis on population distributions and finding statistically significant families of data, leading to an overall shock separation interface level. The wealth of ground test data also allowed a derivation of a Mission Assurance level for the flight. All of the flight shock measurements were below the EOS Terra Mission Assurance level thus contributing to the overall success of the EOS Terra mission. The effectiveness of the statistical methodology for characterizing the shock interface level and for developing a flight Mission Assurance level from a large sample size of shock data is demonstrated in this paper.

## Introduction

In the aerospace industry, the availability of a meaningful valid set of pyroshock test data is often difficult to obtain. Obtaining a large sample size of such data is very rare. However, a large sample size pyroshock test data set was obtained for a newly designed spacecraft separation system which was employed for the EOS (Earth Observing System) Terra NASA mission. On December 18, 1999, NASA launched the EOS Terra spacecraft to low Earth orbit, on a Lockheed-Martin Atlas IIAS (Atlas-Centaur-141) launch vehicle. Due to EOS's truss structure and hard-point spacecraft interface, the pyroshock spacecraft separation system utilized for this mission was a new design. This separation system was test verified through numerous ground test firings, by both the launch vehicle contractor and the spacecraft contractor. This resulted in an unusually large amount of shock test data. The availability of such a test data set allows a statistical evaluation of shock data which is seldom employed. Emphasis will be given to the population distribution of each data set and the proper combination of different data sets. Additionally the binomial distribution will be used to better characterize the separation shock interface level for this particular separation system. In this paper, a comparison is also provided of the actual AC–141 flight shock levels from the spacecraft separation event with the expected shock level that was derived from the assessment of the ground test data.

## Spacecraft Separation System

As part of the Lockheed-Martin Astronautics (LMA) IELV (Intermediate Expendable Launch Vehicle) Program, a 77 in., six point hard-point payload separation system (PSS77) was developed to provide structural attachment of the EOS spacecraft to the launch vehicle's payload adapter (PLA) during launch and ascent, until the operation of the system releases the spacecraft. Since EOS was the first mission using the PSS77, extensive testing of the system was performed by both the launch vehicle contractor (LMA, at Denver) and the spacecraft contractor (LMMS, Lockheed-Martin Missiles & Space, at Valley Forge).

The PLA is an inverted conical skin-stringer-ring structure. The six shear plates which mount on the forward ring of the PLA (as seen in Fig. 1(a)) correspond to the six nodes or hard-points of the spacecraft. As shown in Figure 1(b), each shear plate is attached to the PLA by a separation stud and nut. The spacecraft hard-points are connected to the shear plates by a number of tension bolts. When the separation nut pressure cartridge fires, the separation stud is released and is caught by the stud catcher assembly. Separation occurs between the PLA and the separation plate (which is now attached to the spacecraft). The separation impulse is provided by springs at each of the six nodes.

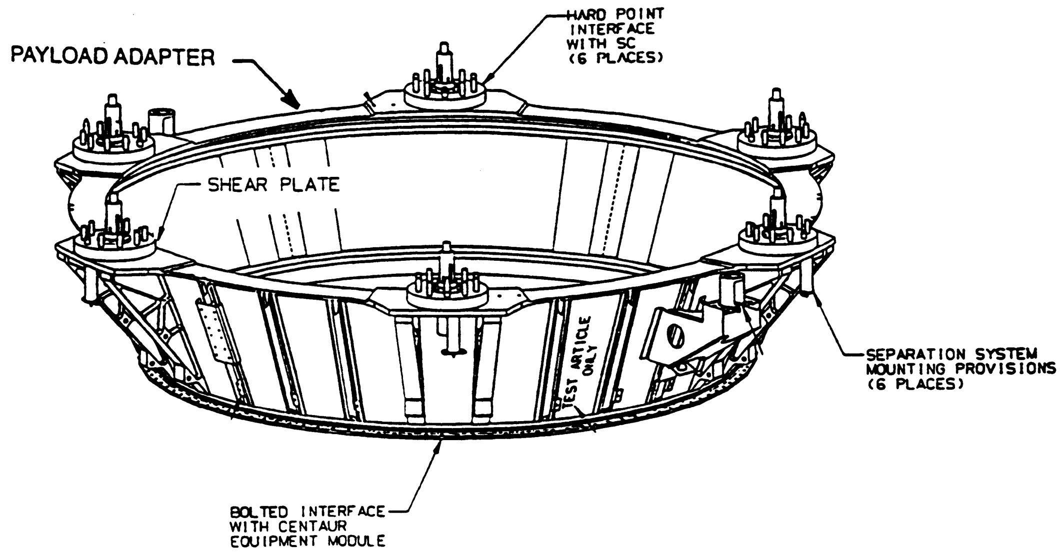



**Figure 1a. Separation System View of Payload Adapter and Shear Plates (Ref. 1)**

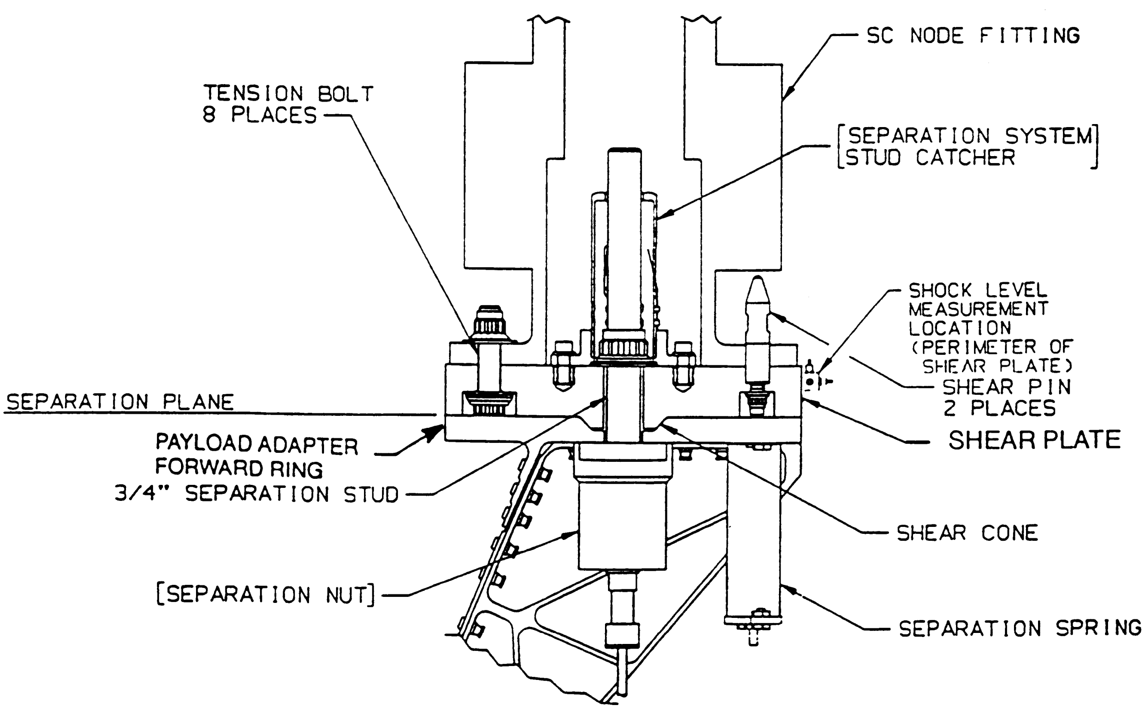



**Figure 1b. Section View of Separation System (Ref. 1)**

## Test Configurations

The test firing of the PSS77 was tested in different hardware configurations at LMA and at LMMS due to different organizational purposes.

The testing at LMA was done to verify the mechanical operation of the PSS77, especially the stud catcher design and to acquire and characterize the pyroshock levels produced by the separation system at various separation stud preload values. A total of twelve test firings were performed over three different test series at LMA (Ref. 1), which occurred from January 1996 through February 1997. Two test firings were performed at LMMS (Ref. 2) in June and July 1996. Since LMMS is the EOS spacecraft contractor, the primary purpose of their testing was to acquire and characterize the pyroshock levels propagating from the spacecraft interface up the spacecraft. Hence two different test configurations were tested.

The LMA test configuration is shown in Figure 2. Approximately one-third of the full spacecraft mass of 11,000 pounds was simulated using the spacecraft stiffness simulator (SCSS). A flight-like PLA, a Centaur Equipment Module (CEM) with avionics components and a stub adapter were utilized. At separation, a mass counterweight was used to achieve the correct flight separation velocity for the SCSS. The PLA, CEM and stub adapter remained attached to the base fixture. Data was obtained at the six shear plate locations, at three PLA locations and at various components of the CEM. LMA acquired their test data on analog tape recorders (Honeywell).

The LMMS test configuration is shown in Figure 3. A full scale spacecraft simulator (11,000 pounds) with mass models for spacecraft instruments was utilized. A short CEM simulator without avionics hardware was used. No stub adapter was present in this testing. An overhead crane suspended the EOS spacecraft and PLA/CEM simulator assembly. At separation, the PLA/CEM simulator dropped approximately 3 in. onto a foam shock absorber pad. Shock data was obtained at the identical six shear plate and three PLA locations (as the LMA testing) and at numerous spacecraft instruments locations. LMMS acquired their test data digitally (Zonic).

## Description of Test Series

The first series of testing, denoted as LMA 1-5, consisted of five separation firings. This testing was performed at LMA’s Denver (Waterton) test facility, as were all the other LMA test series. Testing occurred from January 1996 through April 1996. Various stud preloads were tested (ranging from a very low value of 10,900 pounds to a high value of 24,000 pounds). Both developmental and qualified stud catchers were employed in this series as the stud catcher performance was being evaluated. (A sixth test, LMA 6, was also performed in this series. The purpose of LMA 6 was to measure the effect of ordnance sequencing on the shock levels. Although firing the separation nuts at different times did not significantly affect the shock levels, the data from this test was not utilized in the statistical study of this work. )

The second series of testing is denoted as LMMS 1-2 and occurred at Valley Forge. Testing was performed in June-July 1996. The nominal stud preload of 20,700 pounds were utilized in both of the two test firings.

The third series of testing was denoted as LMA 7-9. These three test firings occurred in September-October 1996. For the CEM avionics boxes, higher fidelity avionics simulators were employed and some new lower fidelity mass simulators were utilized starting with LMA test 7. A low, nominal and high stud preload were tested. Additionally, a positive stud retraction method was added to the stud catcher design starting with LMA test 7.

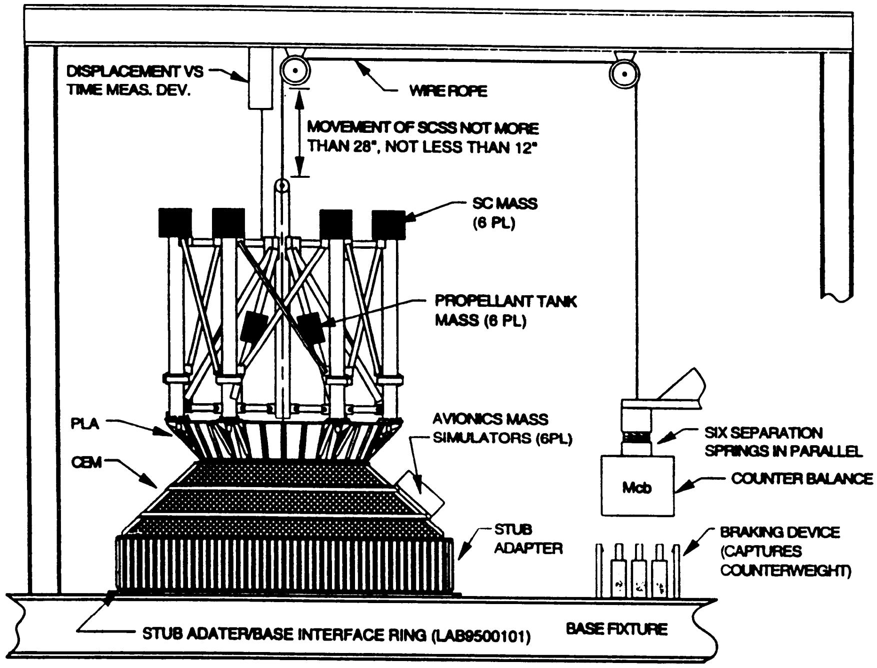
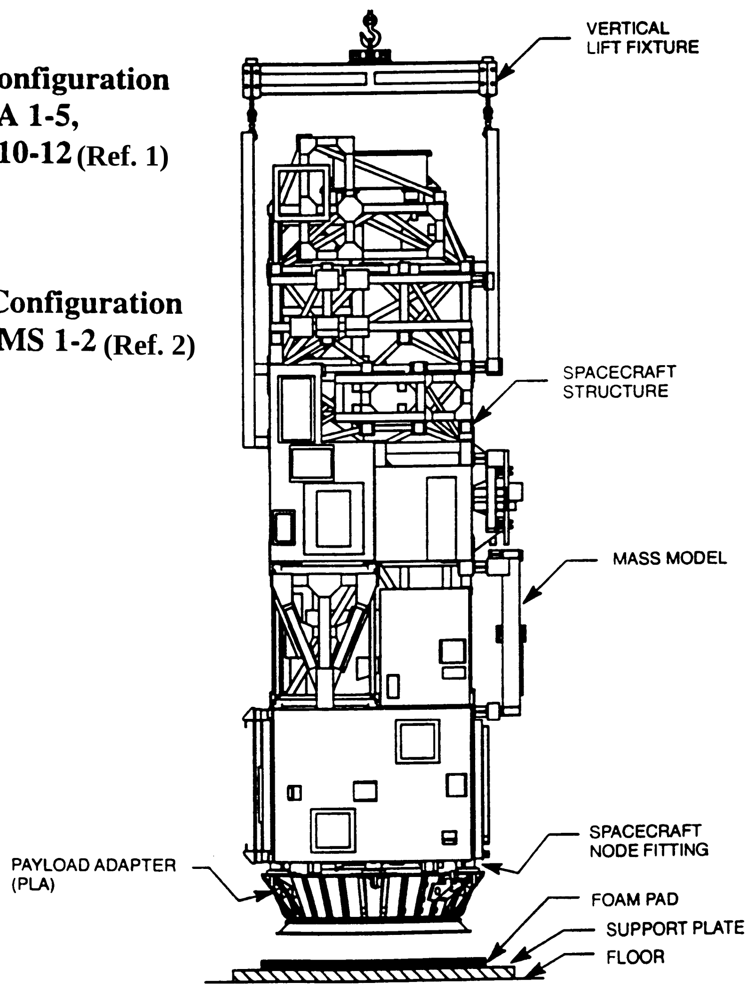



**Figure 2. (above) LMA Test Configuration for Test Series: LMA 1-5, LMA 7-9 and LMA 10-12** (Ref. 1)

**Figure 3. (right) LMMS Test Configuration for Test Series: LMMS 1-2** (Ref. 2)



The fourth and last series of testing was LMA 10-12. These three test firings occurred in February 1997. Again a low, nominal and high stud preload were tested. The separation nuts for LMA 10-12 were taken from a different production lot than all the rest of the EOS test firings. Also, a different CEM was utilized for this testing, along with two more additional CEM simulators.

A summary of the four test series is provided in Table 1. Endevco's 7255A accelerometers were used to measure the shock at the shear plate locations (see Fig. 1(b)) and at the payload adapter (PLA) locations for all four test series. All the shear plate data discussed in this paper is from the axial measurements, which was generally five to ten times larger in magnitude than the radial or tangential measurements at the shear plate locations. Note that unless otherwise stated, the statistical analysis discussed in the next four sections of this paper utilizes the ground test measurements at the shear plate locations to determine the separation interface shock level.

TABLE 1.—SUMMARY OF TEST SERIES

| TEST SERIES | CONFIGURATION & TEST SITE | TEST DATES | NUT PRELOAD VALUES | NUT PRODUCTION LOT |
|---|---|---|---|---|
| **LMA 1-5** | #1 Denver | Jan. 96 - April 96 | very low to high | # 1 |
| **LMMS 1-2** | #2 Valley Forge | June 96 - July 96 | nominal | # 1 |
| **LMA 7-9** | #1 Denver | Sept. 96 - Oct. 96 | low, nominal, high | # 1 |
| **LMA 10-12** | #1 Denver | Feb. 97 | low, nominal, high | # 2 |

## Statistical Analysis of Each Test Series

Each of the four test series was first analyzed to determine its probability distribution. A large data population is generated for each test series by combining all one-sixth octave bands into a single data base by using the method described by Manning (Ref. 3). Each shock response level (at each frequency) was normalized to have zero mean and unit variance. For example, for the LMA 1-5 test series, a normalized database of size 780 was generated (5 tests x 6 measurements per test x 26 one-sixth octave bands (560 to 10,000 Hz) per shock response measurement).

The normalized database is analyzed to determine its probability distribution. The data from each test series was analyzed looking at both the measured data (normal distribution) and the log of the measured data (lognormal distribution). The analysis consisted of plotting probability distributions and histograms and calculating the median (first moment), skew (third moment) and kurtosis (fourth moment) of each normalized database. Duncan (Ref. 4) is a useful resource in determining significantly appropriate skew and kurtosis values as a function of database size.

The conclusion was that the shock test data obtained in each of the four test series was lognormally distributed. This finding is consistent with past practices and with the guidelines of the NASA pyroshock standard (Ref. 5). The large amount of test data available in this testing enabled a statistical basis for the lognormal distribution instead of just assuming it to be true, as is often the case.

Figures 4 to 7 show the shock response measurements for each of the four test series. In all cases, the measured data is fairly repeatable and shows a smaller test to test variability than is often seen for separation shock test data.

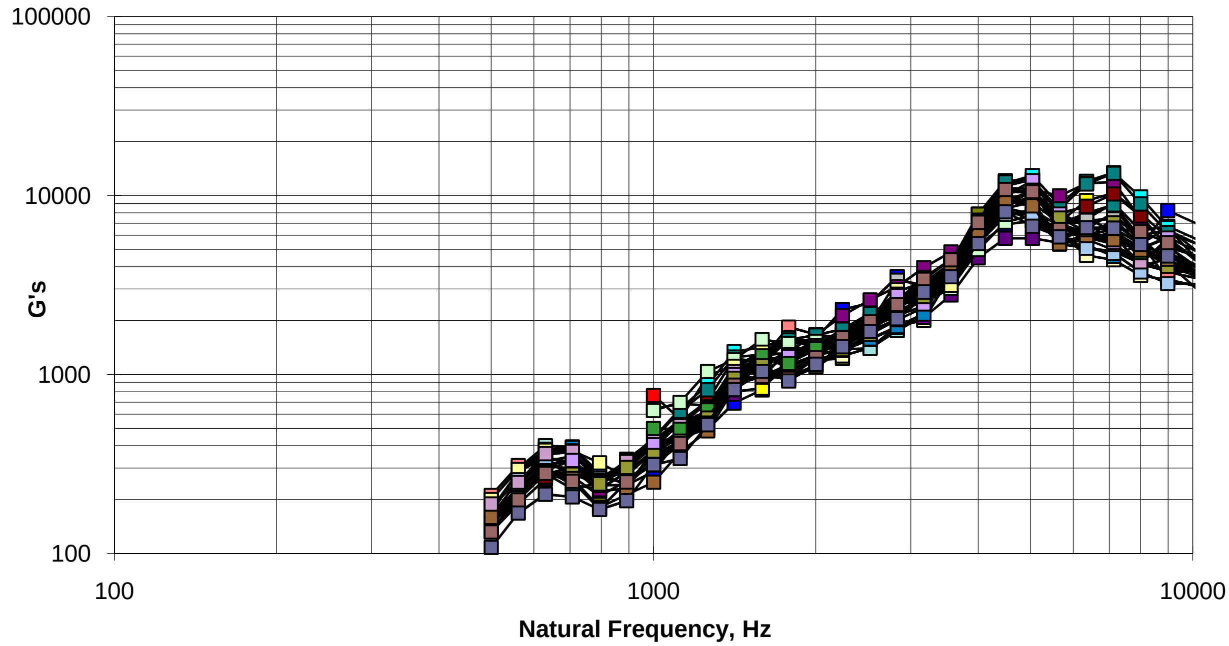



**Figure 4. LMA 1-5**
**Shear Plate Data (30 Measurements)**

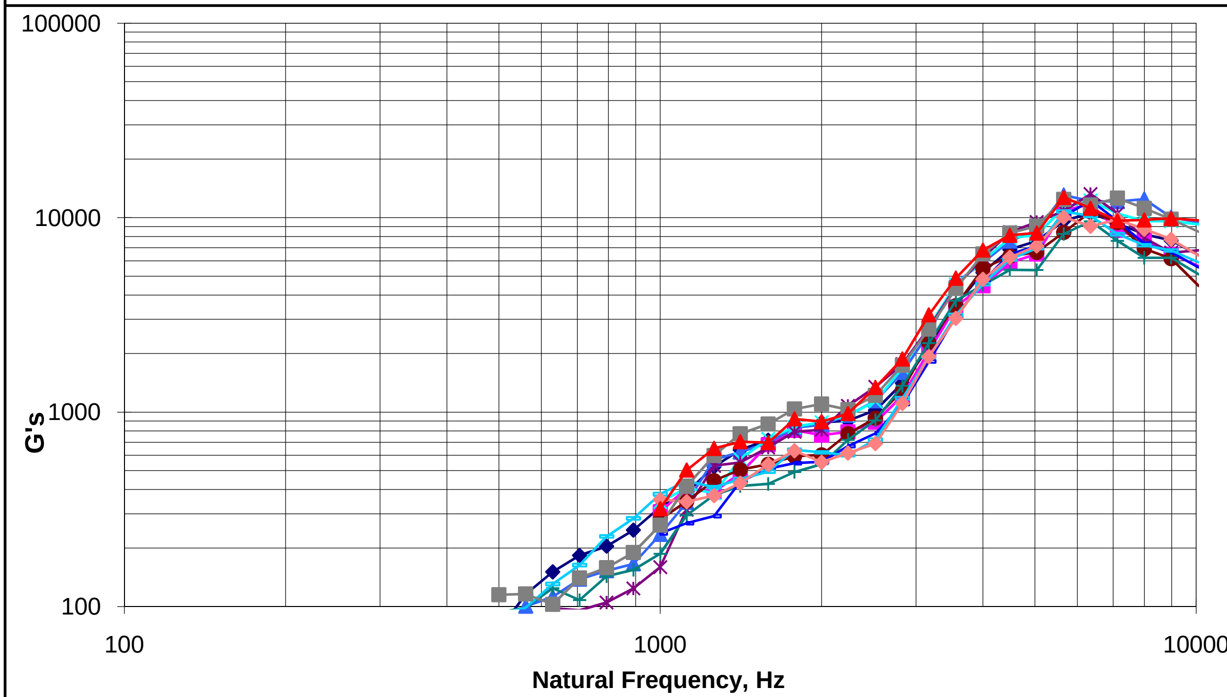



**Figure 5. LMMS 1-2**
**Shear Plate Data (12 Measurements)**

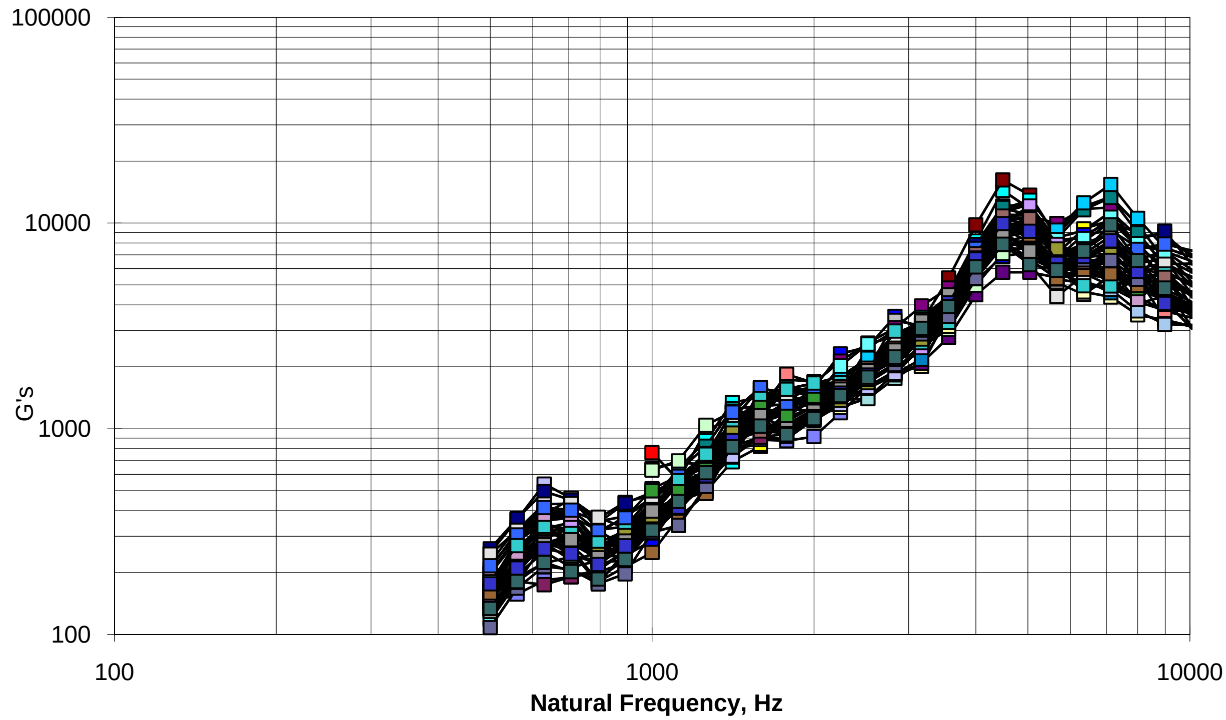



**Figure 6. LMA 7-9**
**Shear Plate Data (18 Measurements)**

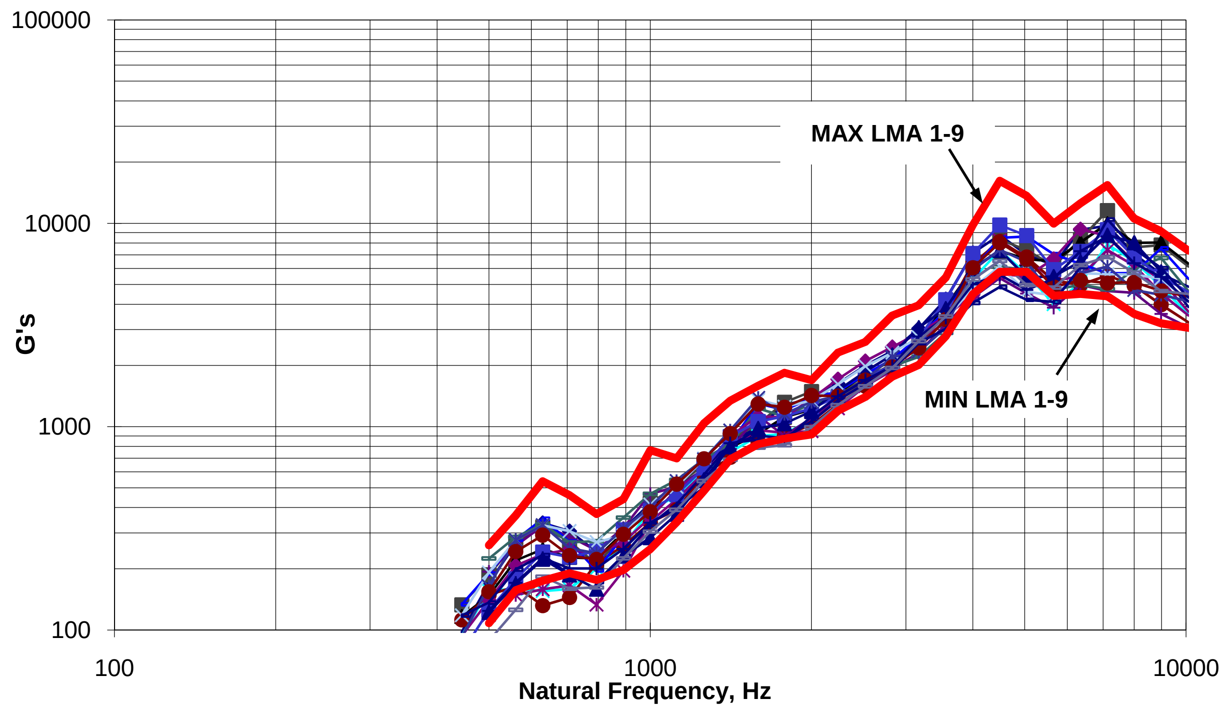



**Figure 7. LMA 10-12**
**Shear Plate Data (18 Measurements)**

# Statistical Combination of Test Series

At this point there are four lognormal series of data. The next question to answer is “Can we statistically combine any or all of these data sets?” before calculating statistical levels. The criterion used for a successful combination was twofold. First, the combined data set must be in itself a lognormal distribution. Secondly, the combination was allowed only if the individual data series has means and standard deviations which were not statistically significantly different with a 95% confidence level. This last criterion was analyzed based on F-testing of the standard deviations and t-testing of the means.

Using these criteria, it was found that it was proper to combine LMA 1-5 and LMA 7-9. The means and standard deviations of these two test series were not statistically significantly different and their combined normalized database was lognormally distributed. Figure 8 shows this combined data set, now denoted as LMA 1-9. The combined data set graphically appears to be one family.

Next, the combination of the new data set LMA 1-9 with LMMS 1-2 was analyzed. It was found to be an invalid combination for two reasons. First, the combined distribution was not lognormal. Secondly, the individual means were found to be significantly different as defined by the t-testing. Looking at Figures 5 and 8, it appears that there are differences in the shock response between these two data sets (i.e., two high frequency peaks for LMA 1-9 and one high frequency peak for LMMS 1-2) to agree with the statistically conclusion to keep these two sets separate. It is thought that the differences in the two basic test configurations cause this result.

Finally, the combination of data sets LMA 1-9 and LMA 10-12 was analyzed. In this case the combined distribution was lognormal and the F-test of the standard deviations passed. However, the t-testing of the means were found to be significantly statistically different and thus this combination was not allowed. Looking at Figure 7, one can see that the general spectral trend of LMA 10-12 is consistent with (the minimum and maximum of) LMA 1-9. However, the LMA 10-12 data is generally between the minimum and the mean of the LMA 1-9 data sets. Thus the statistical conclusions of different means are visualized. It is theorized that the lot to lot variation in the separation nut production lots contributed to this difference. (Note: the separation nuts that were used for the EOS flight is from production lot # 2, which appears to give lower shock levels based on the LMA 10-12 test data.)

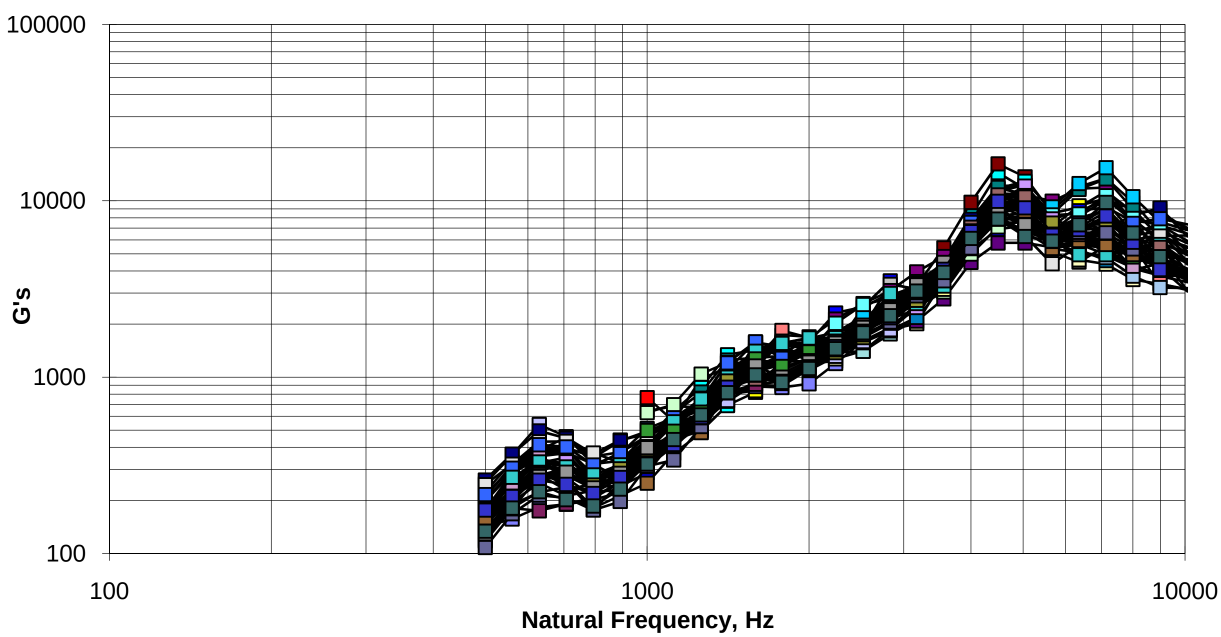



**Figure 8. LMA 1-9**
**Shear Plate Data (48 Measurements)**

## Analysis of Per Nut Firing Level

At this point, three families of shock test data exists, LMA 1-9, LMMS 1-2 and LMA 10-12 (Figs. 8, 5 and 7). Both the LMA and the LMMS test configurations must be considered equally valid with regards to determining a shock interface level. Also since variation in the separation nut production lot should be accounted for both LMA 1-9 (Lot # 1) and LMA 10-12 (Lot # 2) need to be considered. Thus, there are three families of equally valid data.

It was decided to calculate a P95/50 level (using lognormal distribution) for each of the three families. A maximum envelope of these three P95/50 curves was then done to define the maximum expected environment (MEE) for a single separation nut firing. This methodology resulted in a peak shock response level of 13,600 Gs.

## Analysis of Per Flight Level

Since a “successful” flight payload separation system would consists of six separation nuts all firing at or below the MEE level as defined above, it was determined that the per nut MEE level was not sufficient for establishing the spacecraft interface level. For example, if a single nut has a P95/50 probability of success (success defined as being at or below the P95/50 level) then firing six nuts (as in a flight separation) would have only a 74% probability (0.95 raised to the $6^{th}$ power) that none of the six nuts would exceed the P95/50 level.

The binomial distribution (Ref. 6) can be utilized to find the probability of an event happening exactly X times in N trials given the probability that an event will happen in any single trial. Knowing that the desired interface flight MEE is a P95/50 level, a new calculation can be made for an individual nut level. This calculation would result in an individual nut level which would ensure a P95/50 per flight level (firing of six nuts).

One can calculate that a P99.1/50 per nut firing is equivalent to a P95/50 flight firing of six nuts. That is 0.991 raised to the $6^{th}$ power is 0.95.

Therefore a P99.1/50 level was calculated for each of the three valid families of test data. Again the maximum envelope of these three curves was made to calculate the new flight MEE level. Due to the fact that the shock test data within a family was so repeatable, the impact of allowing for the successful firing of all six nuts was only approximately 1 dB. The MEE level was raised from 13,600 Gs (per nut firing) to 15,200 Gs (per flight), as a result.

After allowing for a one-third octave shift in frequency to account for possible hardware stack up variation, the flight MEE level was closely enveloped to define the final Interface Control Document (ICD) level. This ICD level peaks at 16,100 Gs. The ICD specification is shown along with the flight MEE for the three families in Figure 9.

The final ICD level was a significant reduction over the contractor’s proposed final level, and its implementation for the EOS Terra program resulted in saving NASA several million dollars in potential requalification costs of the spacecraft components.

As a check of reasonableness, the maximum envelope of all 78 shock test measurements was determined and plotted against the maximum envelope of the three flight MEE curves of Figure 9. Figure 10 shows that very similar levels are derived by the maximum enveloping technique and the statistical techniques for this EOS shock test data base. This similarity is due to: (1) the unusually large sample size (78 measurements) of test data, and (2) the relatively small test to test variability (within each test family) of the shock data (as compared to typical shock test data variability). Other shock test databases could yield different results depending on its test to test variability and the number of test measurements.

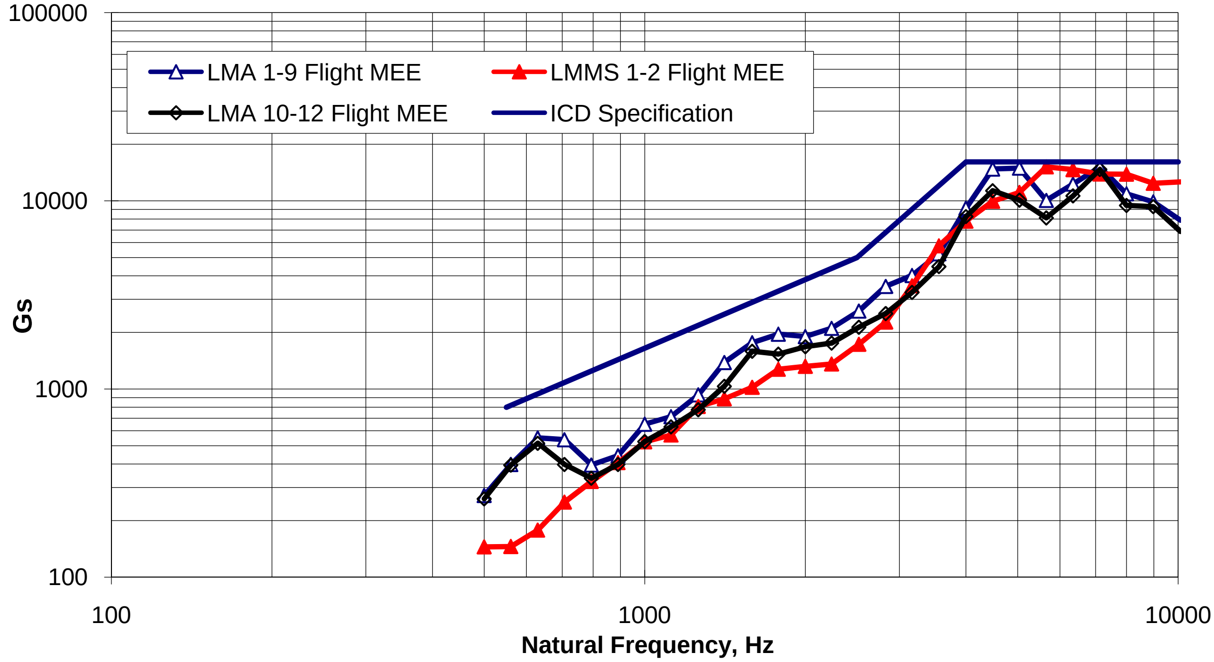



**Figure 9. Comparison of 3 Flight Maximum Expected Environments (MEE) versus Interface Specification**

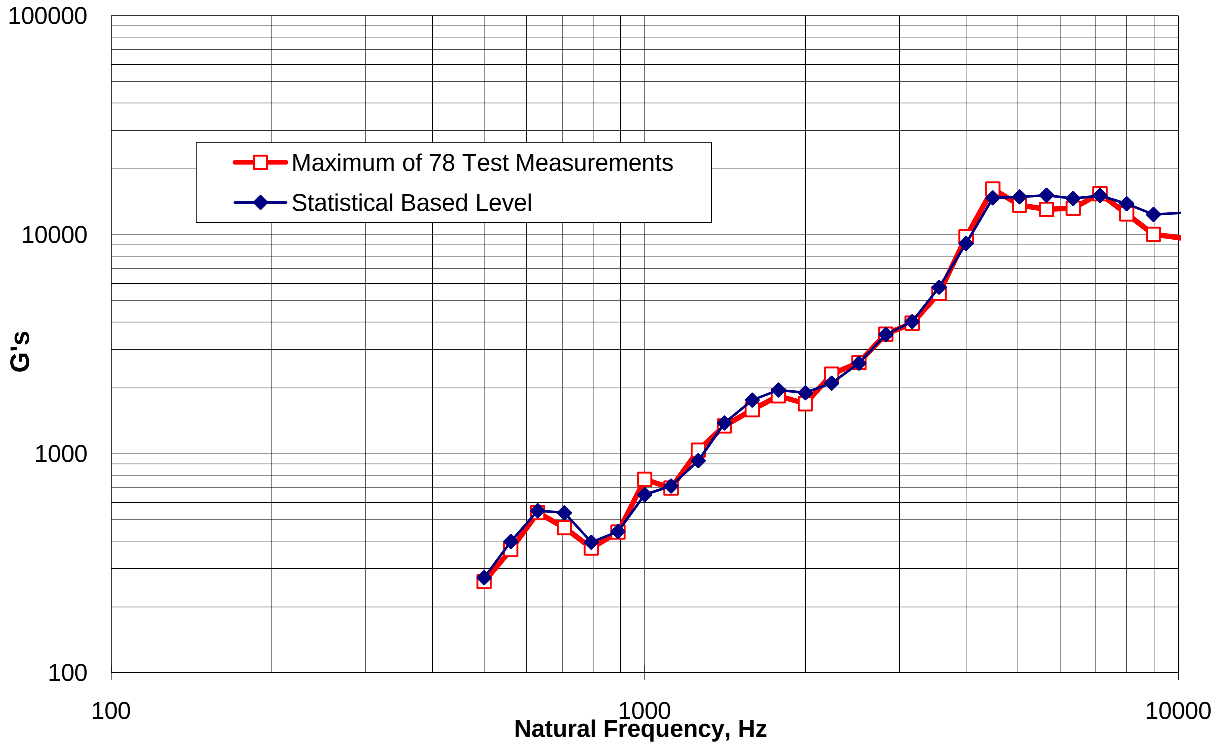



**Figure 10. Comparison of Maximum Enveloping Levels with Statistical Levels**

## Atlas-Centaur-141 Flight Data Analysis

In order to verify the flight shock levels, five AC–141 flight shock measurements were obtained on the payload adapter (PLA) for the spacecraft separation event (Ref. 7). The five measurements consisted of three in the axial direction, and one each in the tangential and radial directions. These flight measurements were utilized as a means to determine whether the amplitude of the shock separation event was within expected limits.

Prior to launch a Mission Assurance shock level was developed from the ground test data in order to establish an extreme expected flight shock level to which the actual flight shock levels from the spacecraft separation event could be compared. Since the flight data was measured on the PLA structure, the Mission Assurance level also needed to be based on this location. From the extensive ground test database, there were a total of 38 PLA axial direction ground test data measurements available (these measurements were in addition to the shear plate measurements described previously).

The PLA ground test data utilized the same statistically based approach as previously described for the ICD level. That is: (1) three valid statistical populations (above 500 Hz due to background noise levels) were established, (2) an extreme expected environment (EEE) for an individual measurement was determined, (3) the binomial distribution was used to calculate a P99/90 per flight level; this is equivalent to a P99.7/90 per individual measurement level, and (4) the EEE per flight levels for the three populations were enveloped to arrive at the statistical based flight level. Per MIL–STD–1540C, the level of the extreme expected environment (EEE), used for qualification testing, is that not exceeded on at least 99% of flights estimated with 90-percent confidence, the P99/90 level.

This EEE level was intended to be the Mission Assurance level, which is the level that an “acceptable flight” should not exceed. The Mission Assurance level would thus be the contractual “not to exceed” level guaranteed by LMA. When the statistical based EEE level was compared to the PLA ground “test data max + 3 dB” it was found that they compared very well, except in the two frequency ranges where the EEE levels were unnecessarily high (+6.6 dB and + 8.5 dB higher than the “maximum of all the PLA ground test data + 3 dB”). Thus the NASA Mission Assurance level was therefore redefined to be the “test data maximum + 3 dB” at all frequencies (instead of the more elaborate statistical based level). (Note: the differences at the two frequencies are due to relatively large standard deviations of the ground test data which increased the statistical level unrealistically far beyond all the measured ground test data. This affect was magnified due to the lognormal transformation process.) Figure 11 illustrates the comparison of the statistically based P99/90 and the test data “maximum + 3 dB” levels. From this figure it is obvious that the statistical based level is not realistic in the two frequency ranges indicated. Thus, a lesson learned is that it is always important to look at the range of actual data for check of reasonableness, especially when dealing with lognormal transformations.

This new level was then frequency shifted by a one-third octave band and tightly enveloped to derive the NASA Mission Assurance level. This NASA level compared well with the LMA-derived mission assurance level that was eventually implemented into the official vehicle contract agreement for the EOS Terra mission. The NASA and LMA (labeled as “EOS Terra”) Mission Assurance levels are shown in Figure 12.

EOS Terra flight measurements were made at the payload adapter region and are compared in Figure 12 to both the EOS Terra (LMA) Mission Assurance and the NASA recommended Mission Assurance levels. All flight data were below the Mission Assurance levels signifying that the AC-141 spacecraft separation event was an acceptable event and resulted in shock levels within allowable limits relative to excessive shock levels which could damage the spacecraft. The flight axial direction data measured higher than radial and tangential direction measurements.

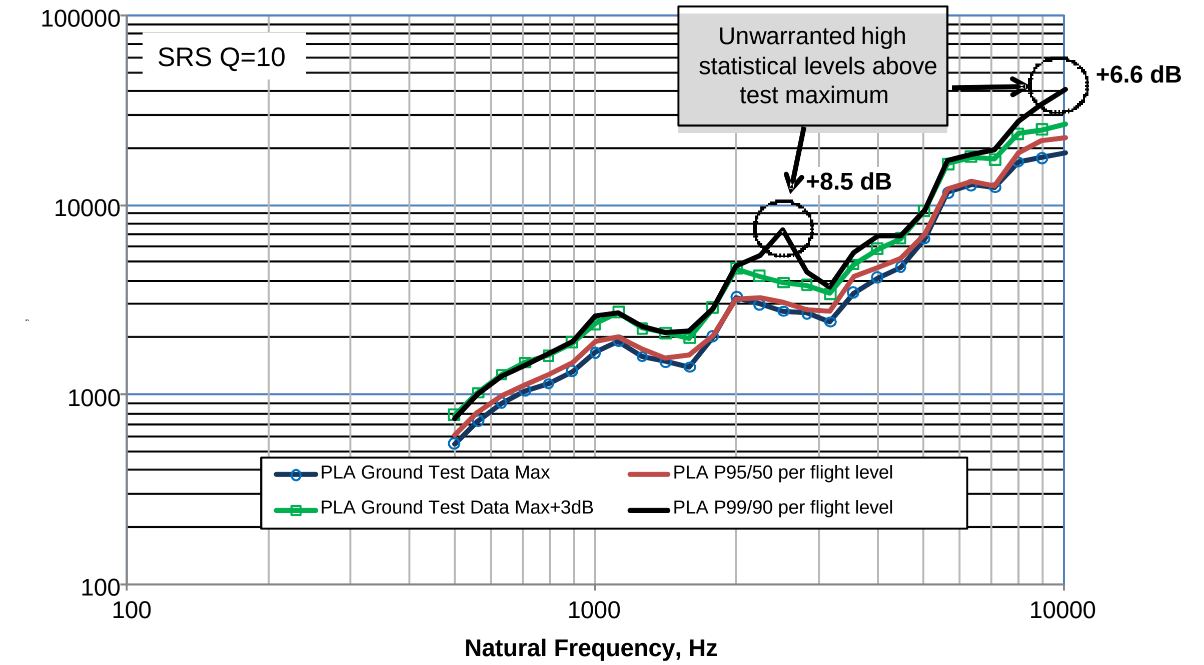



**Figure 11. Comparison of EOS Terra PLA Statistical and Maximum Levels**

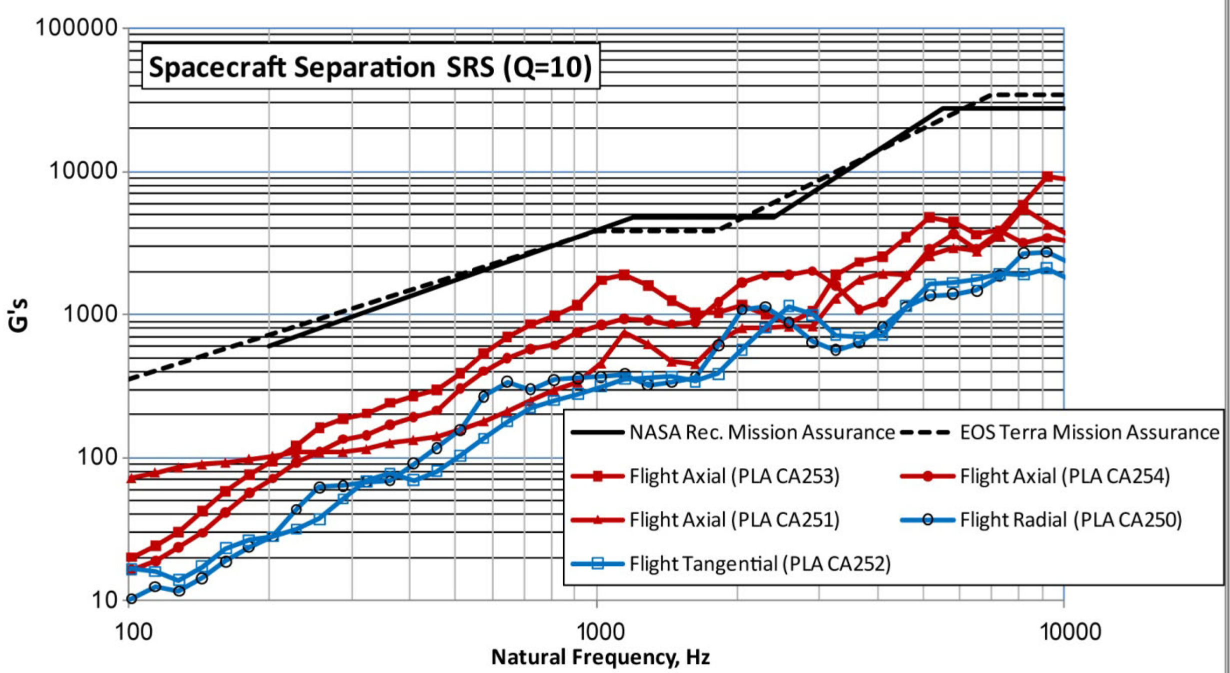



**Figure 12. Comparison of EOS Terra Flight PLA Measurements with Mission Assurance Levels**

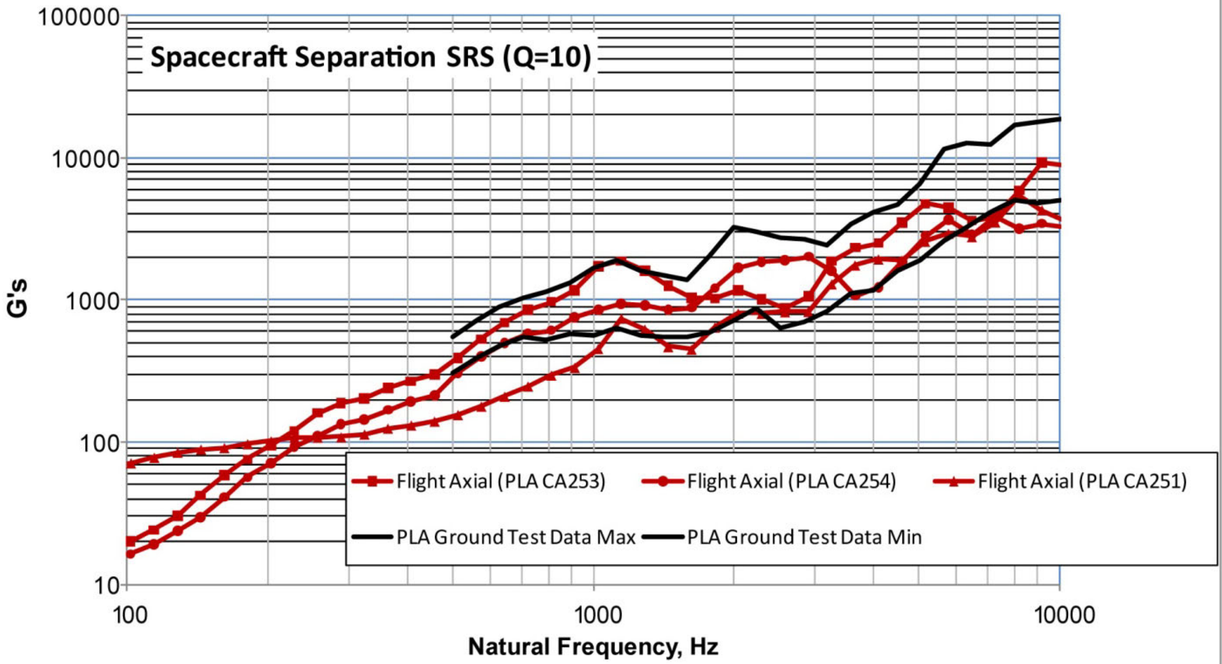



**Figure 13. Comparison of EOS Terra Flight PLA Measurements with PLA Ground Test Data**

The same payload adapter flight data compared very well with the minimum and maximum of the PLA ground test data as shown in Figure 13.

## Conclusions

The sample size is typically small for aerospace shock test data. This often forces the engineer to make assumptions on its population distribution and utilize conservative margins or methodologies in determining specifications. For example, the MEE is often derived by taking the maximum envelope of a limited amount of shock data and adding 3 to 6 dB. For the case of the EOS payload separation shock event, a large amount of shock test data was available which allowed for some unique statistical analysis and a more accurate definition of the interface shock specification.

A description of the methodology employed on the EOS shock test data and the rationale for using it is provided in this paper. The EOS test series data for the shear plate measurements was analyzed and shown to be lognormally distributed for all four test series. Statistical checks were employed to validate when it was proper to combine test series data. It was found to be valid for only one combination. Finally, the binomial distribution was utilized to go from a per nut MEE level to a per flight MEE level which determined the final interface shock specification for the EOS spacecraft.

This methodology resulted in the flight MEE curves and the ICD specification as shown in Figure 9. This ICD specification represents the expected spacecraft separation interface source shock level which in turn is utilized to design and qualify the spacecraft's components.

A similar statistical methodology was employed on the PLA ground test measurements to determine the Mission Assurance level. This Mission Assurance level was a contractual agreement between NASA and LMA which served as a basis of determining whether the actual AC-141 flight spacecraft separation event resulted in reasonable expected flight shock levels. Ultimately it was assessed that the ground data “Test Max + 3 dB” level was the better level, compared to the statistical level, from which to base the NASA Mission Assurance level. The statistically based level had two SRS levels that were unrealistically high due to the large standard deviations and subsequent lognormal transformations of the data.

Actual flight shock measurements at the PLA location were obtained during the AC-141 flight (Ref. 7). As shown in Figure 12, the flight shock levels were below the Mission Assurance level which was indicative of an acceptable spacecraft separation event for this mission, contributing to a successful EOS Terra mission. For this separation system event the flight shock data in the axial direction was higher than for the radial and tangential directions.

Figure 13 illustrates a unique comparison of extensive ground test data sets with the flight data at the same PLA location. The flight shock measurements were comparable in both level and spectral shape to the ground test data.

Further information on the EOS shock separation test programs may be found in the LMA (Ref. 1) and LMMS (Ref. 2) contractor test reports.

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**14. ABSTRACT**
The Earth Observing System (EOS) Terra spacecraft was launched on an Atlas IIAS launch vehicle on its mission to observe planet Earth in late 1999. Prior to launch, the new design of the spacecraft’s pyroshock separation system was characterized by a series of 13 separation ground tests. The analysis methods used to evaluate this unusually large amount of shock data will be discussed in this paper, with particular emphasis on population distributions and finding statistically significant families of data, leading to an overall shock separation interface level. The wealth of ground test data also allowed a derivation of a Mission Assurance level for the flight. All of the flight shock measurements were below the EOS Terra Mission Assurance level thus contributing to the overall success of the EOS Terra mission. The effectiveness of the statistical methodology for characterizing the shock interface level and for developing a flight Mission Assurance level from a large sample size of shock data is demonstrated in this paper.

**15. SUBJECT TERMS**
Statistical analysis; Pyroshock separation system testing; Spacecraft qualification; Dynamics

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